Satellite Tracking System using Amateur Telescope and Star Camera for Portable Optical Ground Station

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Outline

- Introduction: NODE
- Tracking System Design
- Algorithms for Alignment
- Algorithms for Tracking
- Test Results
- Conclusion

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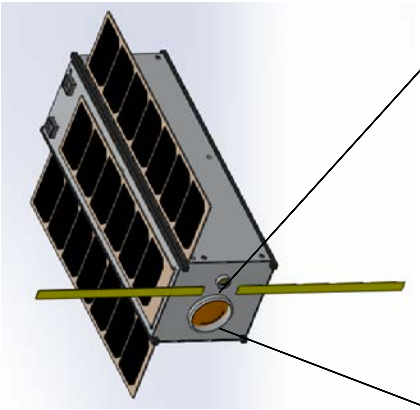
Introduction: NODE

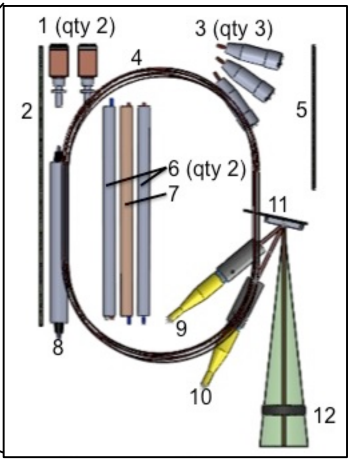
- **Nanosatellite Optical Downlink Experiment (NODE)**[1]
  - Optical communications system for small satellites
  - Technology demonstration on LEO commercial CubeSat in 2017
  - Ability to provide higher data rate at lower cost

Fits onboard the smallest satellites



Credit: Maxim Khatsenko, FLARE, UNP

Small Form-Factor Module



Credit: Ref. 1

Compact, Low Cost Ground Stations

Credit: Celestron: http://goo.gl/ppDSYn

Introduction: NODE

- **NODE Specifications**[1]

Link Parameters		
Data rate	**10-100 Mbps**	
Bit error rate	10^-4 without coding	Conservative baseline for FEC (7% RS planned)
Path length	**<1000 km**	~20 deg elev @ 400 km LEO
Space Segment Parameters		
Size, Weight	**10 x 10 x 5 cm^3, 600 g**	CubeSat payload: 0.5 U
Power	**10 W (transmit mode)**, 1 W (idle)	Entire lasercom payload
Downlink Beam	1550 nm, **0.12° (2.1 mrad) FWHM**	Radiometric constraint for 10 Mbps
Beacon Detector	CMOS camera (silicon)	Ground-station-relative pointing knowledge
Ground Segment Parameters		
Apertures	**RX: 30 cm**, beacon: four at 2 cm each	Mount capable of tracking LEO object
Comm. Detector	Commodity APD/TIA Module	**Operating at 300 photons/bit (no exotic detectors)**
Pointing	Coarse: TLE, Fine: tip/tilt FSM	Detector size demands fine stage

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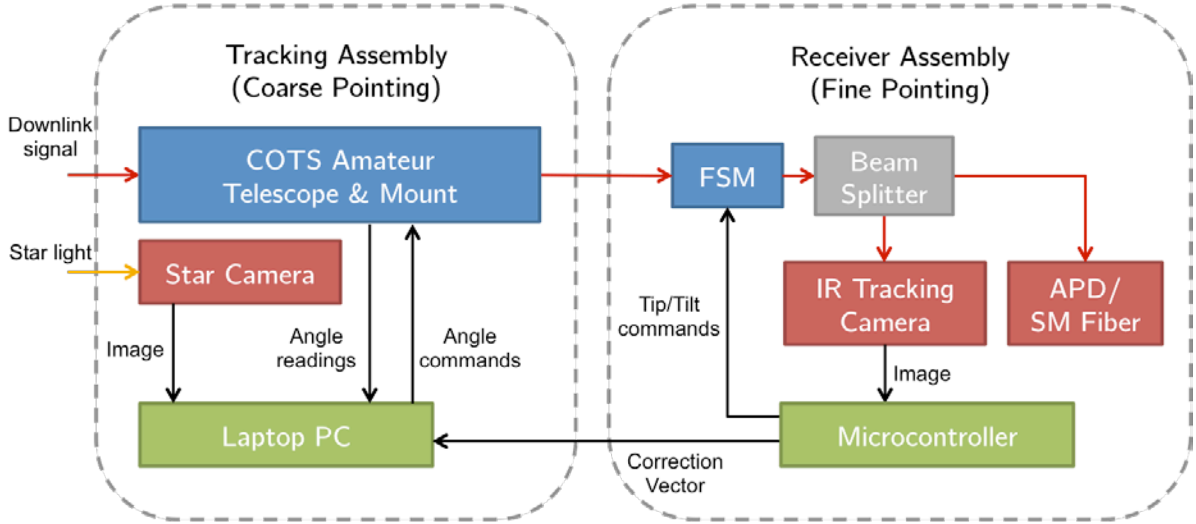
Tracking System Design

- **Ground Station Architecture**



- **The capability of the tracking system (coarse pointing) is validated by tracking the International Space Station (ISS)**

ISS Tracking System

- **Tracking System Specification**

Telescope (CPC 1100)		
Apertures	28 cm	
Focal Length	2.8 m	
Mount Type	Azi-Alt Mount	
Max. Slew Rate	3.5 deg/sec	
Detector Size	3.8 mm x 2.9 mm	Orion StarShoot USB Eyepiece II
FOV	**282 arcsec x 212 arcsec**	
Star Camera (iNova PLB-Mx2)		
Focal Length	35 mm	Edmund 35mm C Series
Detector Size	4.8 mm x 3.6 mm	
FOV	**7.8 deg x 5.9 deg**	
Exposure Time	100-400 ms	

- **Goal: Track the ISS within the narrow FOV of the telescope (282 arcsec x 212 arcsec)**

Telescope Alignment

- **Must determine attitude quaternion between telescope frame and Earth frame (ECEF)**
- **CPC 1100 provides embedded alignment methods**
  - Users must manually point the telescope to known stars
  - Accuracy is not reliably quantified and highly depends on user ability
- **For robust and quantifiable results, we use a star camera for alignment**
  - Does not require manual pointing
  - User does not need to identify stars

Hardware setup on top of MIT Building 37.

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Algorithms for Alignment

- **Three core algorithms for alignment acquisition using star camera**

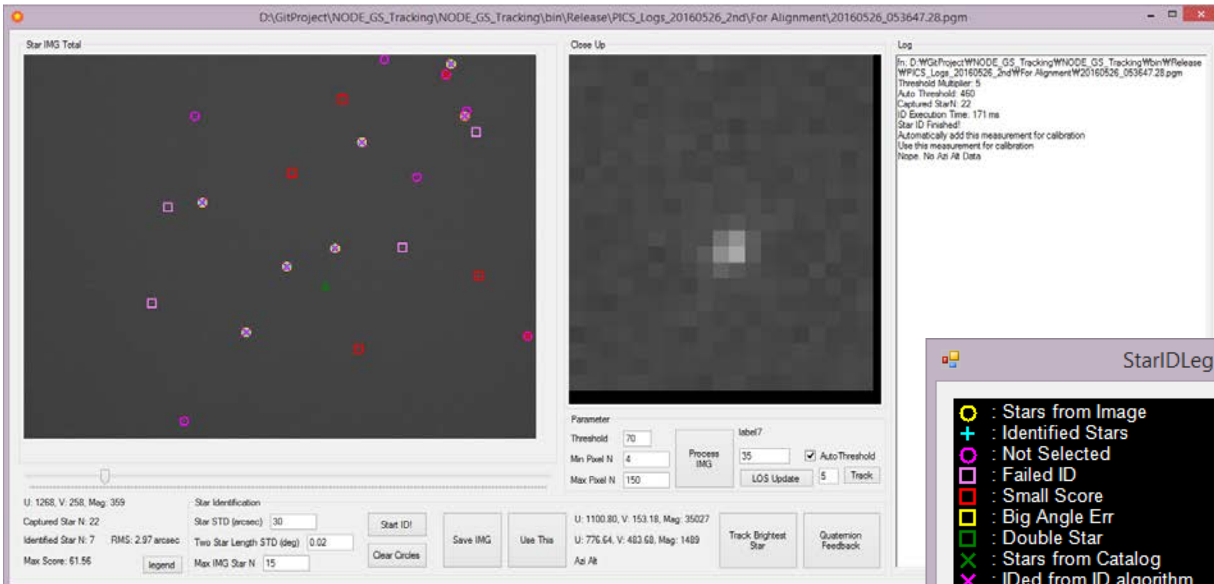
1. Star Identification Algorithm
   - Figure out which are the stars captured in the star camera images
   - Same as the key algorithm for spacecraft star trackers

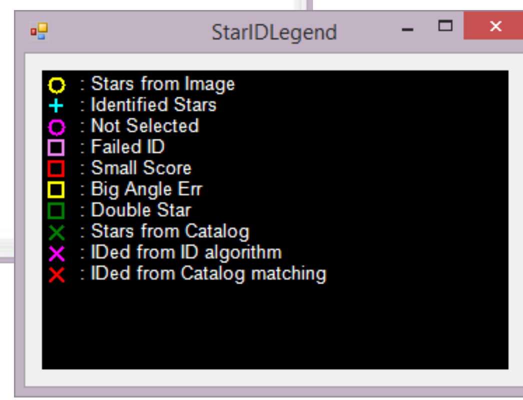
2. Coarse Alignment Calculation
   - Calculate the alignment attitude quaternion without any prior information
   - The result does not guarantee optimality

3. Fine Alignment Calibration
   - Obtain the optimal alignment quaternion using a nonlinear least squares approach
   - Use the results from the coarse alignment calculation as the initial value

Star Identification

- **A correlation-based 3D star pattern matching algorithm proposed by Yoon et al.[2,3] is used.**





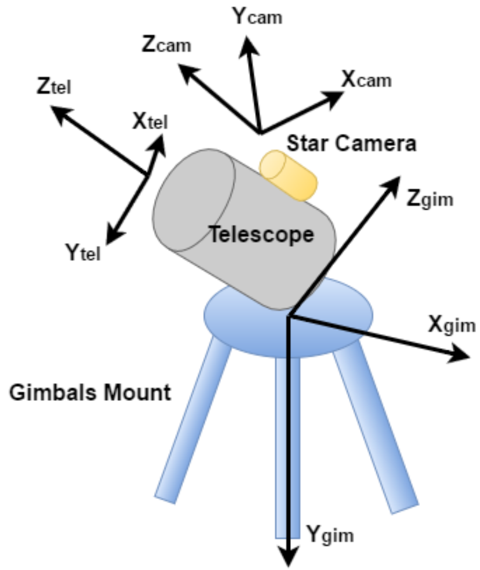
User interface of star tracking software developed in-house for telescope alignment.

Coarse Alignment Calibration

- **The attitude quaternion from the J2000 (ECI) frame to the star camera frame is**

$$\bar{q}_m = \bar{q}_n \otimes {}^{cam}\bar{q}_{tel} \otimes {}^{tel}\bar{q}_{gim} \otimes {}^{gim}\bar{q}_{ecf} \otimes {}^{ecf}\bar{q}_{j2k}$$

$\bar{q}_m$	Quaternion measurement from star camera
$\bar{q}_n$	Measurement noise quaternion
${}^{cam}\bar{q}_{tel}$	Needs to be estimated
${}^{tel}\bar{q}_{gim}$	From Azi-Alt angle
${}^{gim}\bar{q}_{ecf}$	Needs to be estimated
${}^{ecf}\bar{q}_{j2k}$	From IERS model and time



Coarse Alignment Calibration

- **For i-th and j-th measurement pair, and if more than 3 measurement pairs are available,**

$${}^{ecf}\bar{q}_{m,i} \otimes {}^{ecf}\bar{q}_{m,j}^{-1} = \begin{bmatrix} A\left({}^{cam}\bar{q}_{tel}\right) & 0 \\ 0 & 1 \end{bmatrix} {}^{tel}\bar{q}_{gim,i-j} \quad \Rightarrow \quad {}^{cam}\bar{q}_{tel}$$

by QUEST[4] algorithm

$${}^{ecf}\bar{q}_{m,i}^{-1} \otimes {}^{ecf}\bar{q}_{m,j} = \begin{bmatrix} A\left({}^{gim}\bar{q}_{ecf}^{-1}\right) & 0 \\ 0 & 1 \end{bmatrix} {}^{tel}\bar{q}_{gim,-ij} \quad \Rightarrow \quad {}^{gim}\bar{q}_{ecf}$$

by QUEST[4] algorithm

Fine Alignment Calibration

- **Using the error quaternions** $\bar{q} = \delta\bar{q} \otimes \hat{\bar{q}}$**, the vector part of measurement error quaternion can be approximated as**

$$\delta\vec{q}_{m,i} = \vec{q}_{n,i} + \delta\,{}^{cam}\vec{q}_{tel} + A\left({}^{cam}\hat{\vec{q}}_{gim,i}\right)\delta\,{}^{gim}\vec{q}_{ecf}$$

- **This is the form of**

$$\delta\vec{y}_k = H\delta\vec{x}_k + \vec{v}$$

- **We can apply nonlinear least squares and iterate it until the residual error converges to < 1 arcsec**
- **In nonlinear least squares, the initial value is important for its convergence**
  - Results from Coarse Alignment Calibration used as the initial value of the iteration

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Algorithms for Tracking

- **Desired Gimbal Angle and Rate**
  - Calculate the desired gimbal angle and rate to track a satellite (paper)
- **Gimbal Control Law**
  - CPC 1100 only takes motor angle rate as the command for fine tracking
  - The proper gimbal rate commands should be calculated to compensate the angle error as well

$$\dot{z}_c = \dot{z}_d + \frac{1}{T_s}(z_d - z_r)$$

$$\dot{t}_c = \dot{t}_d + \frac{1}{T_s}(t_d - t_r)$$

z, t : Azi and Alt angle

$(\cdot)_c$: Command rate

$(\cdot)_d$: Desired angle and rate

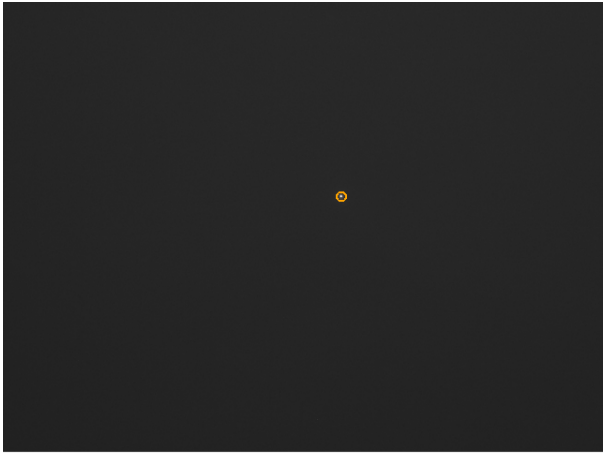
$(\cdot)_r$: Angle reading from telescope mount

T_s : Settling time

  - Ts was selected by trial-and-error as 0.3 sec

Closed-loop Feedback Control

- **ISS tracking tests were conducted to validate tracking performance**
- **Feedback needed to compensate misalignments and unmodeled errors (time and orbit determination)**
  - In final version, a wide-FOV IR tracking camera will be used for feedback
  - Tracking validation is conducted in the visible range for simplicity/ISS imaging
- **Star camera images used as feedback**
  - Images from the telescope's eyepiece camera are available, but FOV is too narrow for initial feedback
  - It is easy to identify the ISS due to the tracking motion – stars are blurred while the ISS is not



ISS captured on the star camera.

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Test Results

- **A sample ISS tracking test**
  - Conducted on 5/26/2016 from 07:14:00 to 07:21:31 UTC on an MIT rooftop
  - Lat: 42.360091 deg, Lon: -71.0914160 deg, Alt: 4 m
  - Maximum elevation angle: 26.75 deg
  - Maximum slew rate: 2086 arcsec/sec
- **Time was synchronized through wireless internet connection using NIST Internet Time Service (ITS)**
  - http://www.nist.gov/pml/div688/grp40/its.cfm
  - The timing might have error up to 1 second
- **Alignment calibration was done prior to the ISS tracking**
- **Feedback from star camera with 3 sec update period**

Alignment Calibration Results

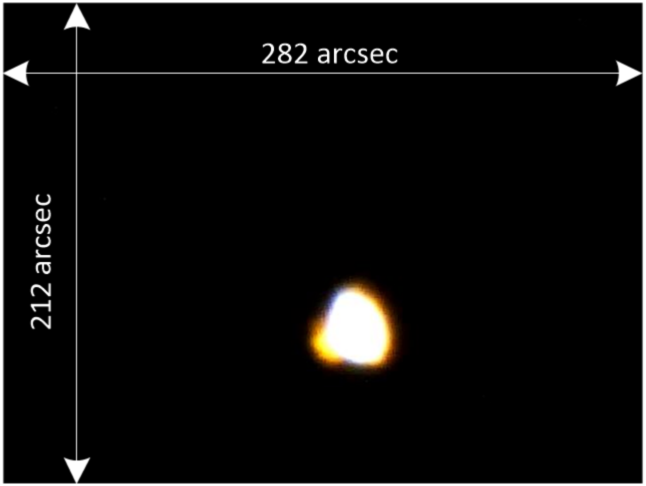
- **Residual error of alignment calibration**

No.	# of Stars	Azi (deg)	Alt (deg)	RMS residual star vector (arcsec)	Residual quaternion, X-axis (arcsec)	Residual quaternion, Y-axis (arcsec)	Residual quaternion, Z-axis (arcsec)
1	12	360.00	30.00	10.01	197.29	-10.45	-106.61
2	9	60.00	30.00	18.93	-100.51	-147.90	-206.55
3	11	180.00	30.00	22.75	-49.46	133.01	-9.29
4	12	288.00	43.75	12.63	73.83	68.71	279.88
5	10	216.00	43.75	17.53	44.35	188.85	273.32
6	10	144.00	43.75	13.81	28.22	-24.09	-7.73
7	9	72.00	43.75	11.16	19.18	-176.87	-204.96
8	10	360.00	43.75	14.95	198.05	-2.35	-70.39
9	7	360.00	57.50	10.55	221.94	29.81	-32.71
10	10	90.00	57.50	16.27	0.91	-125.61	-206.30
11	6	180.00	57.50	20.08	45.55	47.51	100.33
12	9	180.00	71.25	20.51	72.91	11.93	191.01
RMS	n/a	n/a	n/a	16.28	**113.99**	**104.48**	**169.4**

- **Single star centroiding error: < 20 arcsec in cross-boresight axes**
- **Overall quaternion RMS ~110 arcsec in cross-boresight axes**
  - Error is large relative to star camera performance, indicating disturbances

ISS Tracking Results

- **Before the feedback using star camera, the ISS was not captured by the telescope's eyepiece camera (282 x 212 arcsec)**
  - Timing error
  - Alignment error with respect to the inertial frame
- **After star camera feedback, the ISS appeared on the telescope image**

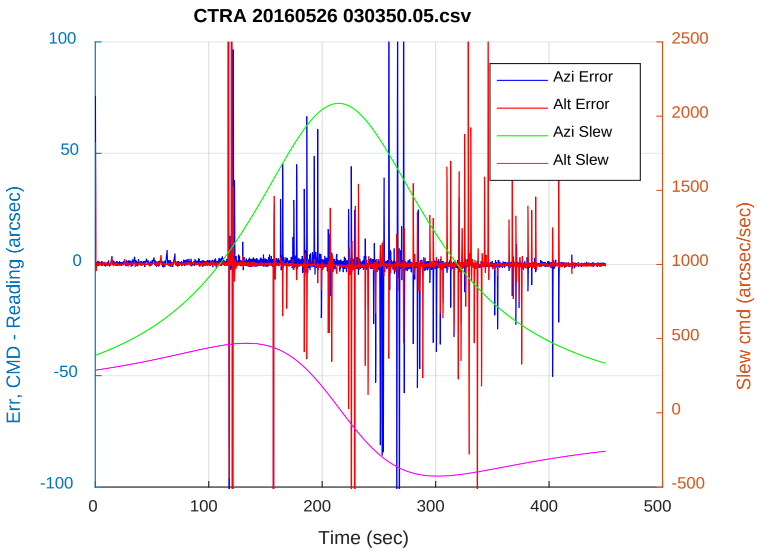


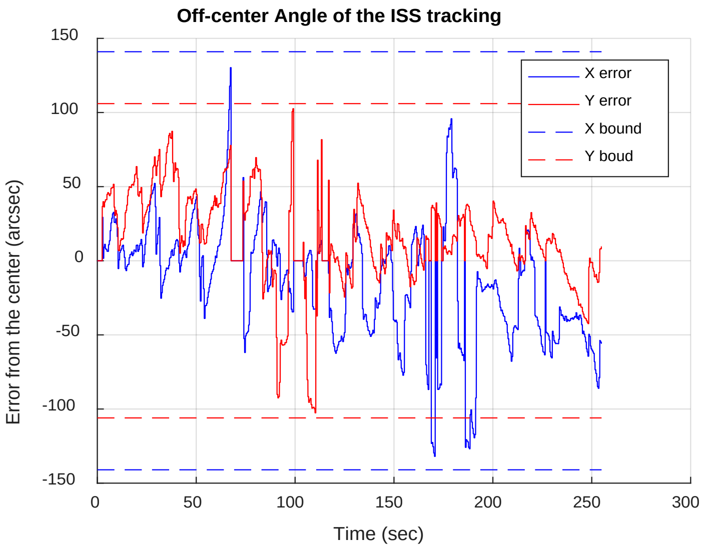
ISS Tracking Video

- **Recorded by the eyepiece camera on the telescope**

Gimbal Angle Tracking History

- **Azi/Alt angle and rate command and tracking error**
  - The RMS tracking error: 42.81 arcsec in X axis and 36.34 arcsec in Y axis





Conclusion and Future Work

- **Conclusion**
  - It is feasible to track a satellite with commercial-off-the-shelf hardware
    - The telescope is an amateur telescope and the star camera is also an amateur astronomy USB camera.
  - The tracking error can be as small as 60 arcsec, so this can provide a coarse pointing stage for the NODE ground station
- **Future Work**
  - The alignment error should be reduced
    - The rooftop of the building was covered by rubber mats to absorb vibrations, but it may cause deformation as the gimbal angles change
    - Star catalog used for the alignment calibration can be updated for proper motion and stellar aberrations
  - Time synchronization should be improved
    - Time sync via internet is not correct enough to track a satellite
    - Time sync using GPS receiver is being considered

References

1. **Clements et al., "Nanosatellite Optical Downlink Experiment: Design, Simulation, and Prototyping," SPIE Optical Engineering, Accepted.**
2. **Yoon et al., "New Star-Pattern Identification Using a Correlation Approach for Spacecraft Attitude Determination," Journal of Spacecraft and Rockets, 48, 1, 182-186, 2011.**
3. **Yoon et al., "New star pattern identification with vector pattern matching for attitude determination," IEEE Transactions on Aerospace and Electronic Systems, 49, 2, 1108-1118, 2013.**
4. **Shuster and Oh, "Three-axis attitude determination from vector observations," Journal of Guidance, Control, and Dynamics, 4, 1, 70-77, 1981.**

Thank you!

Any questions?